AD-A244 959

(2)

Final Report

# Laboratory and Numerical Modeling of Topographic Effects on Time-Dependent Ocean Currents

Office of Naval Research Grant
N00014-89-J-1217



Submitted to

Office of Naval Research
Ocean Sciences Program Directorate
(ONR Code 1122ML)

December 10, 1991





Submitted by

Don L. Boyer

Department of Mechanical and Aerospace Engineering
College of Engineering and Applied Sciences
Arizona State University
Tempe, Arizona

# Final Report

# Laboratory and Numerical Modeling of Topographic Effects on Time-Dependent Ocean Currents

*Office of Naval Research Grant*
*N00014-89-J-1217*



*Submitted to*

*Office of Naval Research*
*Ocean Sciences Program Directorate*
*(ONR Code 1122ML)*

*December 10, 1991*



*Submitted by*

*Don L. Boyer*

*Department of Mechanical and Aerospace Engineering*
*College of Engineering and Applied Sciences*
*Arizona State University*
*Tempe, Arizona*

## Summary

This is the final technical report on the project "Laboratory and Numerical Modeling of Topographic Effects on Time-Dependent Ocean Currents" under Office of Naval Research (ONR) Grant N00014-89-J-1217. The funding level for this project was $356,244 for the period 15 November 1988 - 15 November 1991. The project was the physical modeling component of the ONR Accelerated Research Initiative (ARI) on Flow Over Abrupt Topography. This ARI's principal goal was the development of an improved understanding of the physical and biological environment in the vicinity of isolated seamounts. In particular field experiments and attendant analyses along with numerical modeling and physical simulations of the region in the vicinity of Fieberling Guyot were conducted in this ARI.

The physical models considered a wide range of problems related to the laboratory simulation of the interaction between ocean current systems and isolated topography. In particular the models included appropriate background stratification and rotation, as well as the unsteady nature of background currents (e.g., tidal motions). The studies also considered flow past multiple obstacles in order to assess such effects as the critical separation distances for which topographic features could be considered isolated.

Laboratory studies of the combined baroclinic-barotropic instability of jets in rotating stratified flows were also conducted under this grant. The culmination of these studies was a simulation of the effect of orography on the path of the Antarctic Circumpolar Current.

Finally, numerous other modeling experiments of relevance to physical oceanographic systems were conducted under the grant. One of particular importance to the motion past isolated seamounts concerned the efficiency of oscillating (tidal) currents in boundary layer mixing.

## 2. Overview of Research Findings

This research had a number of complementary long range goals. The first was the development of increasingly realistic physical models of ocean current systems as they pass over and around isolated topography or as they interact with more complex bathymetry. To this end, the comparison of the models with corresponding analytical and numerical models and with oceanic observations was considered an essential supporting goal.

The research conducted was generally directed toward the development of models applicable to the flow in the vicinity of Fieberling Guyot, the seamount for which field observations for the ONR-ARI on Abrupt Topography were taken. As the project developed, however, new directions of fruitful inquiry were suggested and thus the scope of the investigations broadened beyond that originally envisioned. The overview of the research conducted under this grant is thus divided into three sections corresponding to (i) ocean current interactions with isolated topography; (ii) jets in rotating and stratified fluids; and, (iii) other physical modeling experiments. These are now briefly discussed.

### *2.1. Ocean Current Interactions with Isolated Topography*

The original vision of the modeling to be conducted was to investigate the interaction of a spatially uniform oscillatory current superimposed on a mean free stream with a model of Fieberling Guyot. The modeling was to include the appropriate background stratification and rotation. The pertinent similarity parameters for these studies were the Rossby, temporal Rossby, Ekman and Burger numbers and the topographic height to fluid depth ratio. The fluid depth to topography width ratio is not an important similarity parameter as long as the model experiments are conducted in parameter ranges for which the model flows (as are their oceanic counterparts) are hydrostatic.

These initial studies showed that three characteristic flows might be expected in the vicinity of Fieberling; i.e., fully attached, attached lee-side eddies and eddy shedding. The experiments demonstrated that residence times for fluid parcels advecting past, but above the seamount crest,

should be expected to be no greater than twice the advective time-scale (based on the mean free stream speed and the horizontal dimension of the seamount). The experiments clearly demonstrated that residence times can be substantially larger than the advection scale for fluid parcels below the crest and in the lee of the seamount. This phenomenon is associated with the strong return flow toward the seamount for both the attached lee-side eddies and eddy shedding regimes.

The modeling experiments also reproduced anticyclonic loops caused by diurnal tides for fluid parcels advecting over the seamount as found by Genin, Lonsdale and Noble (1989). A ubiquitous feature of the studies is a strong anticyclonic motion in the vicinity of the seamount surface; this result is in good qualitative agreement with numerical models (see Boudra, 1989).

The experiments also investigated upwelling and downwelling in the vicinity of the seamount. This observable is of fundamental importance to biological oceanographers but is not easily measured in the ocean. The modeling experiments demonstrated that upwelling and downwelling characteristics are strong functions of the particular phase of the diurnal tidal cycle.

Recognizing that Fieberling Guyot might not be isolated dynamically from neighboring seamounts (e.g., Fieberling II Seamount and Hoke Guyot), a series of model studies of a rotating, stratified, time-dependent current impinging on two identical obstacles of varying separation distance and orientation to the free stream were conducted. The experiments demonstrated the important nature of obstacle separation and orientation in establishing various characteristic flows. The general conclusion is that at least in the upper levels of the ocean (say above 1500 m) that Fieberling II Seamount and Hoke Guyot are sufficiently far from Fieberling as to have little influence on the flow field in the vicinity of that topographic feature.

As a result of early field operations in the vicinity of Fieberling it became apparent that the mean background flow in the region was very weak and that the principal motions near Fieberling were in response to tidal motions and advecting eddy structures. These observations also demonstrated that large vertical and horizontal shears, as well as jet-like motions, were characteristic features of the current system near Fieberling; Roden (1991). The physical modeling

program thus "adjusted course" and began investigating motion systems with weak or no mean background flow.

An experimental program conducted with the 13 m turntable in Grenoble, France, demonstrated clearly that an oscillatory barotropic motion in the vicinity of an isolated topographic feature drives an anticyclonic mean current above the topography, this current was parameterized in terms of the system parameters to allow extrapolation to oceanic flows. A numerical model employing the quasigeostrophic potential vorticity equation was shown to be in good agreement with the experiments. The laboratory results were also in good agreement with a numerical model of Wright and Loder (1985).

An experimental program concerned with pure oscillatory currents was also conducted for linearly stratified flows in the vicinity of an isolated topography. The experiments were conducted at fixed Burger and Ekman numbers for ranges of the Rossby (Ro) and temporal Rossby ($Ro_t$) numbers. Characteristic flow patterns were described and presented on a Ro against $Ro_t$ flow regime diagram. Rectified anticyclonic currents were developed *for all characteristic flows.* Such rectified flows were similar to those observed at Fieberling; see Genin et al. (1989) and Eriksen (1991). The physical experiments demonstrated that for superinertial frequencies (i.e., $Ro_t > 1$), a resonance phenomenon enhances the strength of the current near the surface while at subinertial frequencies (i.e., $Ro_t < 1$), bottom trapping is observed. The laboratory findings support observations of Eriksen (1991) near Fieberling Guyot suggesting that superinertial frequencies are more pronounced near the ocean surface.

## 2.2. *Jets in Rotating and Stratified Fluids*

Jets are ubiquitous features of ocean current systems and thus their study as phenomena themselves or as they interact with topography are important matters in physical oceanography. In the present project, zonal jets with vertical and horizontal shear were established in a circular tank filled with a linearly stratified rotating fluid by withdrawing fluid from the central region of the tank near the free surface and returning the fluid along the tank periphery. The stability characteristics

of the jet were investigated as a function of the system parameters. The nature of the combined baroclinic-barotropic instability of the jet was depicted on a Rossby against Richardson number regime diagram. Such jets can be used to investigate shear flows impinging on isolated topography.

Experiments were also conducted to assess the influence of an azimuthal ridge aligned along the jet axis on the stability of the jet. The experiments demonstrated clearly that an along jet axis ridge tends to stabilize the jet. It was also demonstrated that the ridge, in the linearly stratified case has less control on stabilizing the motion than corresponding experiments with a two-layer jet.

The source-sink driven jet described above was shown to be equivalent to a wind-driven ocean model jet. Using realistic topography, a model of the Southern Ocean bathymetry on the path of the Antarctic Circumpolar Current (ACC) was developed. This model was in good agreement with oceanic observations of Gordon, Molinelli and Baker (1978). One interesting result was the demonstration of the importance of the Eltanin and Udintsev fracture zones in the vicinity of 135°W on the character of the ACC east of the Drake passage.

### 2.3. *Other Physical Modeling Experiments*

Numbers of other physical modeling experiments were at least partially supported under the subject grant. One such study was the completion of a series of experiments and attendant analyses on the effects of rotation on the growth of the convective boundary layer. One interesting aspect of these studies was the observation of laboratory vortices similar in spatial and temporal characteristics to dust devils observed in the desert Southwest.

The grant also supported the completion of a series of laboratory studies on the collapse and evolution of lens eddies in two-fluid rotating systems. These results may have some application in better understanding long-lived interior oceanic eddy systems.

Motivated by mixing events observed near Fieberling Guyot, experiments concerning the characteristics of mixing in an originally linearly-stratified non-rotating fluid by the oscillation of a vertically oriented right circular cylinder were conducted. The linear density profile evolves into a

non-linear one owing to the non-uniform mixing of the fluid with height caused by the variation in turbulent eddy sizes with depth as forced by the oscillating cylinder. By measuring the rate of increase of potential energy stored in the fluid, it is shown that estimates of the vertical mixing coefficient can be obtained.

## References


Boudra, D. 1989 "Isopycnal modeling of flows associated with seamounts." TopoNews II, Newsletter of ONR Accelerated Research Initiative, Flow Over Abrupt Topography, 5-6.

Eriksen, C. 1991 "Observations of amplified flows atop a large seamount." *J. Geophys. Res.*, in press.

Genin, A., Noble, M. and Lonsdale, P.F. 1989 "Tidal currents and anticyclonic motions on two North Pacific seamounts." *Deep Sea Res.*, **36**, 1803-1816.

Gordon, A.L., Molinelli, E.J. and Baker, T. 1978 "Large scale relative dynamic topography of the Southern Ocean." *J. Geophys. Res.*, **83**, 3023-3032.

Roden, G. 1991 "Mesoscale flow and thermohaline structure around Fieberling seamount." *J. Geophys. Res.*, **96**, 16,653-16,672.

Wright and Loder 1985 "A depth-dependent study of the topographic rectification of tidal currents." *Geophys. Astrophys. Fluid Dyn.*, **31**, 169-220.


## 3. Archival Publications

### *3.1. Ocean Current Interactions with Isolated Topography*

Boyer, D.L., Zhang, X. and Davies, P.A. 1989 Time-dependent, rotating, stratified flow past isolated topography. In <u>Mesoscale/Synoptic Coherent Structures in Geophysical Turbulence</u> (Ed. J.C.J. Nihoul and B.M. Jamart), Elsevier, Amsterdam, 655-670.

Boyer, D.L. and Zhang, X. 1990 "The interaction of time-dependent rotating and stratified flow with isolated topography." *Dynamics of Atmospheres and Oceans*, **14**, 543-575.

Boyer, D.L. and Zhang, X. 1990 "Motion of oscillatory currents past isolated topography." *Journal of Physical Oceanography*, **20**, 1425-1448.

Davies, P.A., Spence, G.S.M. and Boyer, D.L. 1991 "On the interaction of an isolated obstacle with a rotating stratified shear flow." *Geophysical and Astrophysical Fluid Dynamics*, **58**, 57-74.

Boyer, D.L., Chabert d'Hieres, G., Didelle, H., Verron, J., Chen, R. and Tao, L. 1991 "Laboratory simulation of tidal rectification over seamounts; homogeneous model." *Journal of Physical Oceanography*, **21**, 1559-1579.

Zhang, X. and Boyer, D.L. 1991 "Current deflections in the vicinity of multiple seamounts." *Journal of Physical Oceanography*, **21**, 1122-1138.

Zhang, X. and Boyer, D.L. 1992 "Tidal flow in the vicinity of an isolated topography." *Journal of Physical Oceanography*, under review.

*3.2. Jets in Rotating and Stratified Flows*

Chen, R. and Boyer, D.L. 1989 "The stabilizing effect of topography on jets in rotating two-layer flows." In *Proceedings*, Fourth Asian Congress of Fluid Mechanics, University of Hong Kong, H.K., 9-12.

Boyer, D.L. and Chen, R. 1990 "Jet instability and the stabilizing effect of topography on jets in a two-layer rotating systems." *Geophysical and Astrophysical Fluid Dynamics*, **52**, 45-70.

Chen, R., Boyer, D.L. and Tao, L. 1991 "Stability characteristics of jets in linearly-stratified, rotating fluids." *Geophysical and Astrophysical Fluid Dynamics*, in press.

Boyer, D.L., Chen, R. and Tao, L. 1991 "Laboratory simulation of bathymetric effects on the Antarctic Circumpolar Current." *Journal of Geophysical Research*, under review.

*3.3. Other Physical Modeling Experiments*

Boyer, D.L., Davies, P.A., Fernando, H.J.S. and Zhang, X. 1989 "Linearly stratified flow past a horizontal circular cylinder." *Philosophical Transactions of the Royal Society*, London, **A328**, 501-528.

Fernando, H.J.S., Boyer, D.L. and Chen, R. 1989 "Turbulent thermal convection in rotating and stratified fluids." *Dynamics of Atmospheres and Oceans*, **13**, 95-121.

Chen, R., Fernando, H.J.S. and Boyer, D.L. 1989 "Formation of isolated vortices in a rotating convecting fluid." *Journal of Geophysical Research*, **94**, 18,445-18,453.

Boyer, D.L., Chen, R. and Tao, L. 1989 "Some laboratory experiments on rotating and/or stratified flow past topography." *Fluid Dynamics Transactions*, Polish Academy of Sciences, **14**, 7-30.

Davies, P.A., Besley, P. and Boyer, D.L. 1990 "An experimental study of flow past a triangular cape in a linearly stratified fluid." *Dynamics of Atmospheres and Oceans*, **14**, 497-528.

Fernando, H.J.S., Chen, R. and Boyer, D.L. 1991 "Effects of rotation on convective turbulence." *Journal of Fluid Mechanics*, **228**, 513-547.

Biolley, F.M. and Boyer, D.L. 1991 "Lens eddies in rotating two-fluid systems." *Geophysical and Astrophysical Fluid Dynamics*, in press.

Boyer, D.L. 1991 "Laboratory and numerical modeling of geophysical systems." In *Proceedings* of Soviet-American Workshop on Numerical Methods in Aerodynamics, Tashkent, Uzbekistan, U.S.S.R., in press.

Tao, L., Boyer D.L. and Chen, R. 1991 "Laboratory simulation of atmospheric motions in the vicinity of Antarctica." *Journal of Atmospheric Sciences*, under review.

Perera, M.J.A.M., Boyer, D.L. and Fernando, H.J.S. 1992 "Mixing induced by oscillatory stratified flow past a right circular cylinder." *Journal of Physical Oceanography*, to be submitted.

Xu, Y., Boyer, D.L. and Zhang, X. 1992 "Oscillatory rotating flow past a cylinder." *Physics of Fluids*, to be submitted.

### *3.4. Reports*

Boyer, D.L. and Zhang, X. 1989 "Some considerations for the laboratory modeling of currents interacting with isolated seamounts." TopoNews II, ONR Accelerated Research Initiative, Flow Over Abrupt Topography, 1-4.

Boyer, D.L. and Zhang, X. 1991 "Laboratory simulation of systems relevant to the flow in the vicinity of Fieberling Guyot." TopoNews IV, ONR Accelerated Research Initiative, Flow Over Abrupt Topography, 11-13.

Zhang, X. and Boyer, D.L. 1991 "Trapped currents in the vicinity of an isolated topography." TopoNews V, ONR Accelerated Research Initiative, Flow Over Abrupt Topography, 31-32.

### *3.5. Theses*

Xu, Yunxiu 1990 "Rotating flow past a laterally oscillating cylinder." M.S. Thesis, Arizona State University, December, 1990.

Perera, M.J.A. Miren. 1991 "Mixing induced by oscillatory stratified flow past a right circular cylinder." M.S. Thesis, Arizona State University, January 1991.

## 4. Meeting Presentations and Seminars

### *4.1. Meeting Presentations*

Boyer, D.L., Chen, R. and Fernando, H.J.S. "Effects of rotation on convective turbulence." Abstract, American Physical Society Meeting, Buffalo, November 1988.

Chen, R. and Boyer, D.L. "The stabilizing effect of topography on jets in rotating two-layer flows." Fourth Asian Congress of Fluid Mechanics, University of Hong Kong, H.K., December 1988.

Davies, P.A., Boyer, D.L. and Fernando, H.J.S. "Wake flows in stratified fluids." Meeting on Waves and Turbulence in Stably Stratified Flows, 3rd IMA Conference on Stably Stratified Flows, University of Leeds, U.K., December 1988.

Zhang, X. and Boyer, D.L. "Unsteady stratified rotating flow past isolated topography." Fifth Arizona Fluid Mechanics Conference, Tucson, February 1989.

Zhang, X. and Boyer, D.L. "The interaction of unsteady stratified rotating flow with isolated topography." American Geophysical Union Spring Meeting, Baltimore, May 1989.

Boyer, D.L. "Laboratory modeling in the vicinity of Fieberling Guyot." ONR-AIR Principal Investigators Workshop on Flow Over Abrupt Topography, Seattle, November, 1989.

Boyer, D.L. "Laboratory and numerical modeling of geophysical systems." Methods in Aerodynamics, Tashkent, Uzbekistan, U.S.S.R., November 1989.

Zhang, X. and Boyer, D.L. "The interaction of oscillatory currents with isolated topography in the presence of background rotation and stratification." American Geophysical Union Fall Meeting, San Francisco, December 1989.

Zhang, X. and Boyer, D.L. "Laboratory experiments concerning multiple seamount interactions." Ocean Sciences Meeting, New Orleans, February 1990.

Zhang, X. and Boyer, D.L. "Steady and oscillatory flow past two-body topography in a rotating stratified fluid." Sixth Annual Arizona Fluid Mechanics Conference, Tempe, February 1990.

Boyer, D.L., Chabert d'Hieres, G., Didelle, H. and Tao, L. "Rectification of oscillatory homogeneous flow over isolated topography." Fifth Colloquium on Modeling of Oceanic Vortices, Dartmouth College, May 1990.

Boyer, D.L., Chabert d'Hieres, G., Didelle, H., Verron, J., Chen, R. and Tao, L. "Laboratory simulation of rectification over seamounts: homogeneous model." Forty-third Meeting of Division of Fluid Dynamics, American Physical Society, Cornell University, November 1990.

Chen, R., Tao, L. and Boyer, D.L. "Laboratory simulation of the effects of the South Ocean topography on the Antarctic Circumpolar Current." Seventh Arizona Fluid Mechanics Conference, Tucson, March 1991.

Perera, M., Boyer, D.L. and Fernando, H.J.S. "Mixing induced by oscillatory stratified flow past a right circular cylinder." Seventh Arizona Fluid Mechanics Conference, Tucson, March 1991.

Tao, L., Chen, R. and Boyer, D.L. "Laboratory simulation of the effects of cooling and orography on the large-scale circulation of the atmosphere in the vicinity of the Antarctic." Seventh Arizona Fluid Mechanics Conference, Tucson, March 1991.

Xu, Y., Boyer, D.L. and Zhang, X. "Oscillatory flow past a right cylinder in rotating system." Seventh Arizona Fluid Mechanics Conference, Tucson, March 1991.

Chen, R., Tao, L. and Boyer, D.L. "Laboratory simulation of the effects of the Southern Ocean topography on the Antarctic Circumpolar Current." American Geophysical Union Meeting, Baltimore, May 1991.

Tao, L., Chen, R. and Boyer, D.L. "Laboratory simulation of the effects of cooling and orography on the large-scale circulation of the atmosphere in the vicinity of Antarctica." American Geophysical Union Meeting, Baltimore, May 1991.

Zhang, X., Boyer, D.L., Chabert d'Hieres, G., Aelbrecht, D. and Didelle, H. "Rectified flow generated by along shore tidal motion." American Physical Society, Scottsdale, AZ, November 1991.

### *4.2 Seminars - D.L. Boyer*

Lavrentyev Institute of Hydrodynamics, Novosibirsk, U.S.S.R., November, 1988

Institute for Problems in Mechanics, Moscow, U.S.S.R., November, 1988

Computer-Aided Design Institute, Moscow, U.S.S.R., November, 1988

Harvard University, Cambridge, MA, February, 1989

University of Arizona, Tucson, AZ, February, 1989

Lamont Doherty Geological Institute, Columbia University, Palisades, NY, April 1991

Institute of Ocean Sciences, Sydney British Columbia, Canada, May 1991

Department of Civil Engineering, University of Dundee, United Kingdom, September 1991

Institute of Fundamental Technical Problems, Polish Academy of Sciences, Warsaw, December 1991